Application

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Title:

BROADLY TUNABLE DISTRIBUTED BRAGG REFLECTOR STRUCTURE PROCESSING

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BROADLY TUNABLE DISTRIBUTED BRAGG REFLECTOR STRUCTURE PROCESSING

CROSS REFERENCE TO RELATED APPLICATIONS

This application relates to concurrently filed, co-pending application U.S. patent application Ser. No. ____09 849,109____, entitled "Vertical-Cavity Surface Emitting Laser (VCSEL) Structure and Method for a Wavelength Tunable Laser" by Yu-Hwa Lo et al., owned by the assignee of this application and incorporated herein by reference.

This application relates to concurrently filed, co-pending application U.S. patent application Ser. No. ___09/849,958___, entitled " Distributed Feedback (DFB) Structure and Method for a Wavelength Tunable Laser" by Yu-Hwa Lo et al., owned by the assignee of this application and incorporated herein by reference.

This application relates to concurrently filed, co-pending application U.S. patent application Ser. No. ____09/849,169____, entitled " Distributed Bragg Reflector (DBR) Structure and Method for a Wavelength Tunable Laser" by Yu-Hwa Lo et al., owned by the assignee of this application and incorporated herein by reference.

BACKGROUND INFORMATION

Field of the Invention

The present invention relates to the field of wavelength tunable semiconductor devices, and particularly to creating broadly tunable wavelength tunable semiconductor devices.

Description of Related Art

Wavelength-tunable lasers serve as a fundamental building block in constructing optical communication and sensing systems. Wavelength-tunable lasers play a central role in particular for dense wavelength division multiplexing (DWDM) systems that form the backbone of today's optical communication network. The term "wavelength-tunable

laser" is typically applied to a laser diode whose wavelength can be varied in a controlled manner while operating at a fixed heat sink temperature. At the 1550 nm wavelength regime on which most DWDM systems operate, a wavelength shift of 0.1 nm corresponds to a frequency shift of about 12.6 GHz. At a given heat sink temperature, the central wavelength of a conventional distributed feedback (DFB) laser diode may be red-shifted by as much as 0.3 nm or about 40 GHz due to the rise in the temperature of the junction by Ohmic losses. In contrast, at a given heat sink temperature, the wavelength of a tunable laser may vary by several nanometers, corresponding to hundreds or even thousands of GHz, covering several wavelength channels on the International Telecommunication Union (ITU) grid. Depending on the physical mechanisms of wavelength tuning, the lasing wavelength can be tuned in either positive (red) or negative (blue) direction. Controlled wavelength tunability offers many advantages over conventional fixed wavelength DFB lasers for DWDM operation. It enables advanced all-optical communication networks as opposed to today's network where optics is mainly used for transmission and the network intelligence is performed in the electronic domain. All-optical networks can eliminate unnecessary E/O and O/E transitions and electronic speed bottlenecks to potentially achieve very significant performance and cost benefits. In addition, a less extensive inventory of wavelength-tunable lasers than of laser with a fixed wavelength is required. Keeping a large inventory of lasers for each and every wavelength channel can become a major cost issue. For advanced DWDM systems, the channel spacing can be as narrow as 50 GHz (or about 0.4 nm in wavelength), with as many as 200 optical channels occupying a wavelength range of

about 80 nm. For the reasons stated above, wavelength-tunable lasers have attracted considerable interest in optoelectronic device research.

There exist different design principles for tunable lasers. Almost all wavelength-tunable laser designs make use of either the change of refractive indices of semiconductor or the change of laser cavity length to achieve wavelength tuning. For the former, common mechanisms for index change include thermal tuning, carrier density tuning (a combination of plasma effect, band-filling effect, and bandgap shrinkage effect), electro-optic tuning (linear or quadratic effect), and electrorefractive tuning (Franz-Keldysh or quantum confined Stark effect). For DFB lasers, the wavelength of the laser light propagating in the waveguide is basically determined by the grating period Λ. The free-space lasing wavelength λ is given by $\lambda = 2\, n_{eff}\, \Lambda$, where n_{eff} is the effective index of refraction of the waveguide and Λ is the period for first-order gratings. Accordingly, the change $\Delta\lambda$ in the lasing wavelength λ is directly proportional to the change Δn of the index of refraction n_{eff}.

Accordingly, it is desirable to have structures and methods for generating broadly wavelength tunable semiconductor devices.

SUMMARY OF THE INVENTION

It is an object of the current invention to provide a method for decreasing the spontaneous recombination rate, B, in a DBR thereby increasing the tuning range of the DBR. According to the current invention, this may be achieved by creating electron confinement regions and hole confinement regions in the waveguide of the DBR.

A preferred process according to the current invention achieves this by engineering the band gaps of the DBR waveguide and cladding materials such that an electron confinement region and a hole confinement region are created in the waveguide of the DBR, thereby reducing the recombination rate and increasing the tuning range. Preferably, the materials selected for use in the DBR may be lattice matched.

Optionally, alternate methods according to the current invention may create two or more thin electron confinement regions and/or two or more thin hole confinement regions. In some cases, multiple thin confinement regions may be used to take advantage of strain compensation in thinner layers thereby broadening the choices of materials appropriate for use in the broadly tunable DBR.

Optionally, a variety of DBR designs comprising graded materials and/or graded interfaces may be used to provide effective electron and/or hole confinement regions may be created using alternate methods according to the current invention

Optionally, a variety of optical devices such as lasers and/or integrated opto-electronic devices may be created using an alternate method according to the current invention by incorporating one or more conventional processing steps.

Advantageously, the current invention enables the production of DBRs and lasers with broad wavelength tuning ranges making the use of tunable wavelength devices more attractive for a variety of optical networking applications.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is an architectural diagram illustrating a first embodiment of a three-section DBR structure in accordance with the present invention.

FIG. 2 is an architectural diagram illustrating a second embodiment of a three-section DBR structure in accordance with the present invention.

FIG. 3 is an architectural diagram illustrating a third embodiment of a three-section DBR structure in accordance with the present invention.

FIG. 4 is an architectural diagram illustrating a fourth embodiment of a three-section DBR structure in accordance with the present invention.

FIG. 5 is an architectural diagram illustrating a fifth embodiment of a three-section DBR structure in accordance with the present invention.

FIG. 6 is an architectural diagram illustrating a sixth embodiment of a three-section DBR structure in accordance with the present invention.

FIG. 7 is an architectural diagram illustrating a seventh embodiment of a three-section DBR structure in accordance with the present invention.

FIG. 8 is an architectural diagram illustrating a first embodiment of a VCSEL structure in accordance with the present invention.

FIG. 9 is an architectural diagram illustrating a second embodiment of a VCSEL structure in accordance with the present invention.

FIG. 10 is an architectural diagram illustrating a third embodiment of a VCSEL structure in accordance with the present invention.

FIG. 11 is an architectural diagram illustrating a fourth embodiment of a VCSEL structure in accordance with the present invention.

FIG. 12 is an architectural diagram illustrating a fourth embodiment of a VCSEL structure in accordance with the present invention.

FIG. 13 is an architectural diagram illustrating a first embodiment of a DFB structure in accordance with the present invention.

FIG. 14 is an architectural diagram illustrating a third embodiment of a DFB structure in accordance with the present invention.

FIG. 15 illustrates a band gap diagram and a layer structure for a preferred embodiment in accordance with the present invention.

FIG. 16 illustrates a band gap diagram and a layer structure for an alternate embodiment of the current invention comprising multiple thin electron confinement regions and multiple thin hole confinement regions in accordance with the present invention.

FIG. 17 illustrates an alternate embodiment of the current invention with a graded electron confinement layer and a graded hole confinement layer in accordance with the present invention.

FIG. 18 illustrates a band gap diagram and layer structure for an alternate embodiment in accordance with the present invention.

FIG. 19 illustrates a band gap diagram and layer structure for an alternate embodiment in accordance with the present invention.

FIG. 20 illustrates an alternate embodiment of the current invention using an intermediate barrier layer to assist in the creation of electron-hole isolation in accordance with the present invention.

FIG. 21 illustrates a grating layer in a cross sectional view of a typical DBR structure in accordance with the present invention.

FIG. 22 illustrates an alternate embodiment of the current invention with a grating layer comprised of grooves on the device surface in accordance with the present invention.

FIG. 23 is a flow chart illustrating the process for creating a broadly tunable DBR in accordance with the present invention.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

FIG. 1 is a structural diagram illustrating a first embodiment of a three-section DBR-based laser structure **10** for a wavelength tunable laser. The DBR laser structure **10** has three main sections, a gain or active region **1**, a waveguide layer **2**, and a carrier reservoir structure **3** placed either above or below the gain layer **1**. One of ordinary skill in the art should recognize that additional layers can be added to the DBR laser structure **10** without departing from the spirits in the present invention. A grating **4** is formed that extends originally from the waveguide layer **2**. The positioning of the grating **4** can be placed below or above the waveguide **2** and the gain region **1**. A waveguide layer **6** is typically placed adjacent to the gain layer **1** and above the carrier reservoir structure **3**. The carrier reservoir structure **3** is part of the waveguide and extends continuously across DBR laser structure **10**.

The DBR laser structure **10** is intended to illustrate a sample structure. Other conventional details, such as contacts and a substrate layer can be added without departing from the scope in the present invention.

An isolation region **7** separates electrical current from leaking between a gain section I_1 **8** and a phase section I_2 **9**. The gain section I_1 **8** is a current pumping into the quantum wells for the active region **1**. An isolation region **11** separates electrical current from leaking between the phase section I_2 **9** and a DBR section I_3 **12**. The phase section **9** provides electrical current I_2 that changes the reflective index of the medium, which in turn changes the phase. The third section is the DBR section I_3 **12**. The currents I_2 **9** and I_3 **12** are used for λ wavelength tuning range. The current I_2 **9** assures continuous tuning. However, without the ability to change current I_3 **12**, the resulting graph would show a step function between λ and I_3 **12**. To overcome the step curve, the currents I_2 **9** and I_3 **12** are adjusted in tandem to obtain smooth continuous tuning and curve. A laser beam can be generated in the direction of **14** or **15**.

FIG. 2 is an architectural diagram illustrating a second embodiment of a three-section DBR structure **20** for a wavelength tunable laser. In the DBR structure **20**, a carrier reservoir structure **21** extends from a first region, or the phase section I_2 **9**, to a third region, or the DBR section I_3 **12**. Preferably, the carrier reservoir structure **21** complies with the order in the vertical direction. The combination of all the layers should form a single mode waveguide. The carrier reservoir structure **21** has a higher bandgap than the bandgap of the active layer 16, thereby minimizing light absorption. FIG. 3 is a structural diagram illustrating a third embodiment of a three-section DBR structure **30** for a wavelength tunable laser. In the DBR structure **30**, a carrier reservoir structure **31** is present in the DBR section I_3 **12**.

FIG. 4 is a structural diagram illustrating a fourth embodiment of a three-section DBR structure **40** for a wavelength tunable laser. In this embodiment, the gain section I_1

8 is swapped with the phase section I_2 **9** as shown in FIG. 1. The DBR structure **40** has a phase section I_1 **41** and a gain section I_2 **42**. Optionally, the phase section I1 **41** and the gain section I_2 **42** can be coated to alter the reflectivity. It is apparent to one of ordinary skill in the art that the gain section **8**, the phase section **9**, and the DBR section **12**, can be re-arranged in various combinations and orders.

FIG. 5 is an architectural diagram illustrating a fifth embodiment of a three-section DBR structure **50** integrated with a semiconductor optical amplifier (SOA) for a wavelength tunable laser. The three sections of the gain section I_1 **8**, the phase section I_2 **9**, and the DBR section I_3 **12** make up a tunable laser **51**, which is integrated with a SOA I_4 **52**. The integrated DBR structure with an integrated SOA **50** increases the optical power. An isolation region is placed between the DBR I_3 **13** and the SOA **52** to prevent current leakage. The SOA **52** has identical properties as the gain section **11**. An antireflective coating (AR) **54** is placed at the end and adjacent to the SOA **52**. In the SOA **52** section, a waveguide **6b** extends upwardly from near the top of the waveguide **6**, a gain medium **1b** also extends upwardly from near the bottom of the waveguide **6**, and a line **4c** extends straightly from the grating **4**. The line **4b** is at the same or substantially the same height as a line **4c**. The gain medium **4b** and the waveguide **6b** serve to repeat a gain medium layer and a waveguide layer, although the quantum well in the gain medium **1** may be different from the quantum well in the gain medium **1b**. For example, the gain medium **1** could have a 30 to 40 nm shift wavelength shift relative to the gain medium **1a**.

In the integrated DBR structure **50**, there are four current inputs, the gain section I_1 **8**, the phase section I_2 **9**, and the DBR section I_3 **12**, and the SOA section I_4 **52**. The

composition of the first three current inputs, the gain section I1 **8**, the phase section I2 **9**, and the DBR section I3 12, constitutes the tunable laser **51**. The light from the DBR section **12** is integrated with the SOA section **52**. A principle difference between an amplifier and a laser is that the amplifier generates a traveling wave in one direction, rather than bi-directional. Some portion of light from the DBR I_3 **12** of the laser is passed to the SOA **52**, which has a gain section to amplify the received light. The light from the SOA **52** is transmitted outward in one direction, with the AR **54** preventing light signal from entering into the AR **54**, or the SOA **52**.

FIG. 6 is an architectural diagram illustrating a sixth embodiment of a three-section DBR structure **60** with an external modulator. The three-section DBR structure **60** has the gain section **8**, the phase section **9**, the DBR section **12**, and a modulator section **61**, with an anti-reflective coating **63** placed adjacent to the side on the modulator **61**. The first anti-reflective coating **63** can be selected to have high or typical reflective coating. An isolation region **62** prevents current from leaking between the DBR section 12 and the external modulator **61**. The placement of the gain section **8** can be swapped with the location of the phase section **9**. A tunable laser operates in either a direct current (DC) or near DC level. The external modulator has a quantum well, and is driven by a voltage for modulation. In the modulator **61** section, a waveguide **6c** extends upwardly from near the top of the waveguide **6**, a gain medium **1c** also extends upwardly from near the bottom of the waveguide **6**, and the line **4c** extends straightly from the grating **4**. The line **4b** is at the same or substantially the same height as a line **4c**. The gain medium **4c** and the waveguide **6c** serve to repeat a gain medium layer and a waveguide layer. The quantum well in the modulator **61** can be different from the other quantum wells to

increase the modulation characteristics, such as the quantum well in the gain medium **1** may be different from the quantum well in the gain medium **1c**. The gain medium **1** could have, for example, a 30 to 40 nm shift wavelength shift relative to the gain medium **1a**.

FIG. 7 is an architectural diagram illustrating a seventh embodiment of a three-section DBR structure **70**. The three-section DBR structure **70** has a DBR-1 **71**, a gain section **72**, a phase section **73**, and a DBR-2 **74**. A grating **75** extends in the DBR-1 **71** section, and a grating **76** extends in the DBR-2 **74** section. An isolation region **76** prevents current leakage between the I_3 phase section **73** and the I_4 DBR-2 section **74**. The above embodiments of DBR-based tunable lasers are intended to show several illustrations. One of ordinary skill in the art should recognize that other types of DBR-based combinations can be practiced without departing from the spirits in the present invention.

FIG. 8 is an architectural diagram illustrating a first embodiment of a VCSEL structure **80**. To view from an up-side down perspective, the VCSEL structure **80** has a substrate **81**, a bottom DBR **82**, a center cavity layer **83**, a top DBR **84**, a current I_1 **85**, and a current I_2 **86**. The bottom DBR **82** is formed with a layer A **82a**, a layer B **82b**, a layer A **82c**, and a layer B **82d**, to form a periodic structure. Each layer in the layer A **82a**, the layer B **82b**, the layer A **82c**, and the layer B **82d** is a quarter-wave length. In addition, each A layer and B layer has a different refractive index. For example, if N_A denotes the refractive index of the layer A **82a**, and N_B denotes the refractive index of the layer B **82b**, then $N_A \neq N_B$. The layer A **82a** has an approximately layer thickness of, as

represented by the equation $T_A = \frac{\lambda}{4N_A}$. The layer B **82b** has an approximately layer thickness of, as represented by the equation $T_B = \frac{\lambda}{4N_B}$. The cavity layer **83** has a gain medium or a quantum well. It is apparent to one of ordinary skill in the art that additional A layer and B layers can be added to the bottom DBR 81 without departing from the spirits in the present invention.

Doping materials are injected into the VCSEL **80** structure, such as making a p-doped **84a** into the top DBR **84**, and an n-doped **84c** into the top DBR **84,** with a carrier reservoir structure **84b** in between. When operating a laser, the optical beam or light bounces back and forth between the bottom DBR **82** and the top DBR **84**, and the optical beam exits the VCSEL structure **80** in a direction **87** or a direction **88**.

Two currents, I_1 **85** and I_2 **86**, are injected into the VCSEL structure **80**. The current I_1 **85** adjusts the carrier in the carrier reservoir structure 84b with the current flows in the direction as shown in a loop **89a** through the p **84a** layer, the carrier reservoir structure **84b**, and the n **84c** layer. The current I_2 **86** is used to pump the laser, with the current flows in the direction as shown in a loop **89b** through the layer B **82b**, the layer A **82c**, the layer B **82d**, and the cavity layer **83**. The wavelength is determined by, neglecting any possible thermal effect, with a tuning curve. This is commonly referred to as phase tuning. When increasing the current I_2 **86**, the carrier in the carrier reservoir structure **84b** is increased, thereby increasing the electrons and holes. The index of reflection in the VCSEL structure **80** in turn drops, and thus increases the effective cavity length. When a time t increases, the wavelength is changed. Therefore, by increasing the

current the current I_2 **86**, the carrier compensation in the carrier reservoir structure **84b** is creased, the index of reflection is reduced, the cavity length is effectively increased, and the wavelength is in turn increased.

The wavelength tuning range of the first order is normalized to a central wavelength, represented by the equation $\frac{\Delta\lambda}{\lambda} \alpha \frac{\Delta n}{n} \eta$, where the factor η is determined by the physical location of the carrier reservoir structure **84b** with respect to the center of cavity. A percentage of tuning relates to the percentage of index change. The effect of the design can inject a substantial amount of electrons and holes, resulting in a more substantial change in index for the same amount of current. Our ratio is therefore increased, and hence the wavelength is increased. The closer the carrier reservoir structure **84b** to the cavity, the more effective the tuning range will be.

FIG. 9 is an architectural diagram illustrating a second embodiment of a VCSEL structure **90**. A top DBR **93** has a p-layer **94** and an n-layer **95**. A bottom DBR **92** includes a p-layer A **98**, a p-layer B **97**, a carrier reservoir structure **91**, an n-layer A **96**, and n-layer **95**. The current **86** I_2 flows in the direction as shown in a loop **99a**, through the p-layer **93**, the p-layer **94**, and the cavity layer **93**. The current **85** I_1 flows in the direction as shown in a loop **99b**, through the p-layer A **98**, the p-layer B **97**, the carrier reservoir structure **91**, the n-layer A **96**, and the n-layer B **95**.

FIG. 10 is an architectural diagram illustrating a third embodiment of a VCSEL structure **100**. The VCSEL structure **100** has a reverse doping, with an n-p layer to form a cavity. Instead of an n-p-n formation, the VCSEL structure **100** has a p-n-p formation. A top DBR **101** is formed with an n-layer **102** and a p-layer **103**, with a carrier reservoir

structure **104** placed in between the n layer **102** and the p layer **103**. A bottom DBR **102** is constructed with a cavity layer **105a** that has a gain medium within, an n-layer **105b**, an n-layer **105c**, an n-layer **105d**, an n-layer **105e**. A current source I_2 **108** is used for injecting carrier into the carrier reservoir structure **104**, with current flows in the direction as shown in a loop **106**, through the p-layer **103**, the carrier reservoir structure **104**, and the n-layer **102**. A current source I_1 **109** is used for pumping the laser, with current flows in the direction as shown in a loop **107**, though the cavity layer **105a**, the n-layer **105b**, the n-layer **105c**, the n-layer **105d**, the n-layer **105e**.

FIG. 11 is an architectural diagram illustrating a fourth embodiment of a VCSEL structure **110**. The VCSEL structure **110** has multiple carrier reservoir structure layers, thereby increasing the tuning range and expanding a more complex device fabrication. Another DBR **111** is added to the VCSEL structure **110**, with a carrier reservoir layer **112**, and an n-layer **113**. The current I_2 **86** pumps carriers into the upper carrier reservoir structure **84b**. A current I_3 **114** pumps carriers into the lower carrier reservoir structure **112**, and is used for tuning in the DBR layer **111**, resulting in the increase in the overall tuning range of the VCSEL structure **110**.

FIG. 12 is an architectural diagram illustrating a fourth embodiment of a VCSEL structure **120** for maximizing the factor eta, η. The VCSEL structure **120** is designed with a first DBR **121**, a cavity **122**, and a second DBR **123**, with a carrier reservoir structure **124** placed inside the cavity **122**. A tunnel junction **127** is formed from the combination of the n+ layer **125** and the p+ layer **126**. An active layer 128 is stacked underneath the p+ layer **126**. In VCSEL structure **120**, a single current source I **129**

provides the gain as well as tuning. In other words, the change in a wavelength is proportional to the fluctuation of current I **129**.

FIG. 13 is an architectural diagram illustrating a first embodiment of a DFB structure **130**. The DFB structure **130** has a tunnel junction **131**, a grating layer **132**, with a carrier reservoir structure or tuning layer **133**. The combination of layers in the DFB structure **130** support a single mode operation. When a current I **134** increases above certain threshold, the electrons and holes concentration increases through the tunnel junction **131**, and the index of reflection decrease, and the lasing wavelength decreases. The lasing wavelength is represented by, $\lambda_{DFB} = 2 \times \Lambda \times n$, where the symbol Λ denotes the grating period, and where n denotes the reflective index.

FIG. 14 is an architectural diagram illustrating a third embodiment of a DFB structure **140**. In this embodiment, the tunable laser is turned by 90 degrees. While FIG. 13 is viewed from the direction of light propagation, FIG. 14 shows the cross sectional view of a waveguide. The DFB structure **140** has a grating layer **141**, a carrier reservoir structure **142**, an n-layer **143**, and a quantum well **144**. A current I_1 **145** provides the laser current. The current I_2 **146** provides the tuning current, flowing into the tuning region. The current I_1 **145** determines the gain, and the I_2 **146** current determines the tuning.

FIG. 15 illustrates a band gap diagram and a layer structure for a preferred embodiment of the current invention. In this example, a DBR optical waveguide **315** comprised of two layers **312** and **313** is disposed on top of a first cladding layer **311** and beneath a second cladding layer **314**. Alternately, buried heterostructure (BH) based devices may be constructed according to an alternate embodiment of the current invention. For a BH based device, additional cladding may be provided by the material

surrounding the buried waveguide. Typically, the cladding layers **311** and **314** are doped such that one is n-type and the other is a p-type. According to a preferred embodiment of the current invention, the cladding layers should have opposite doping types. However, the doping types of the two cladding layers **311** and **314** may be swapped without adversely impacting the tunability of the DBR. Similarly, according to a preferred embodiment of the current invention, the relative positions of the layers comprising the electron confinement region **312** and the hole confinement region **313** may be swapped without adversely impacting the tunability of the DBR. According to the current invention, the band gap of the first cladding layer (E_{gc1}) **301** and the band gap of the second cladding layer (E_{gc2}) **309** must both be larger than the characteristic band gap of the electron confinement region (E_{ga}) **304** and the characteristic band gap of the hole confinement region (E_{gh}) **307** in order to create an effective waveguide.

$$E_{gc1}, E_{gc2} > E_{ga}, E_{gb}$$

For the DBR 300, the material used for the electron confinement region **312** must have bandgap offsets from the first cladding layer **311** and from the adjacent hole confinement layer **313** such that the conduction band offsets ΔE_{ca} **302** and δE_c **305** are in excess of the thermal energy, kT, in order to effectively confine electrons:

$$\Delta E_{ca}, \delta E_c > kT$$

where:

k = Boltzmann's constant

T = absolute temperature

Preferably, the offsets ΔE_{ca} **302** and δE_c **305** are greater than 2kT:

$\Delta E_{ca}, \delta E_c > 2kT.$

Similarly, for DBR **300**, the material used for the hole confinement region **313** must have bandgap offsets from the second cladding layer **314** and from the adjacent electron confinement layer **312** such that the valence band offsets **306** and **310** are in excess of the thermal energy, kT, in order to effectively confine holes:

$\Delta E_{vb}, \delta E_v > kT.$

Preferably, the offsets **306** and **310** are greater than 2kT:

$\Delta E_{vb}, \delta E_v > 2kT.$

A variety of materials systems meeting these criteria may be used to create a broadly tunable DBR. For example, InGaAsP lattice matched to InP may be chosen as an electron confinement layer **312** material and used with an InGaAlAs hole confinement layer **313** lattice matched to InP. Alternately, InGaAsSb lattice matched to InP may be chosen as an electron confinement layer **312** material and used with an InGaAlAsSb hole confinement layer **313** lattice matched to InP. According to the current invention, a variety of growth or deposition techniques may be used to create the DBR structure. For example, DBR structures according to the current invention may be created using one or more techniques such as, but not limited to: Molecular Beam Epitaxy (MBE), Chemical Vapor Deposition (CVD) or Metal-Organic Chemical Vapor Deposition (MOCVD).

An optical waveguide according to the current invention may be described according to three dimensions:

1) a first direction parallel to the direction of light propagation,

2) a second direction perpendicular to the first direction and

3) a third direction, perpendicular to both the first and second directions.

For the structure illustrated in FIG. 15, the second direction may be the thickness **320** and the third direction may be a third mutually perpendicular direction, or the breadth **321**. For a structure **300**, the second direction may coincide with the direction of current flow. However, alternate embodiments of the current invention may be implemented with different architectures such that the second direction or thickness does not coincide with the direction of current flow. For example, an alternate embodiment of the current invention may be based on a transverse junction striped laser (TJS). For a TJS based structure, the third direction, or breadth of the structure may or may not coincide with the direction of current flow.

In one embodiment, the thickness of the DBR optical waveguide layer is designed to support a single optical mode. A typical optical waveguide layer according to the current invention is about 2000Å thick. Preferably, the thickness of the layer providing an electron confinement region is greater than the thickness of the layer providing a hole confinement layer. This preference is related to the sp^3 nature of the semiconductors used in the optical waveguide layer which results in a relatively low density of states for electrons in the electron confinement region compared to the relatively high density of states for holes in the hole confinement region. Similarly, it is preferable that the electron confinement barrier δE_c created by the conduction band offset be greater than the hole confinement barrier δE_v created by the valence band offset. For this reason, the minimum size of the electron confinement region should be larger than the minimum size of the hole confinement region in order to prevent electrons from piling up in the electron confinement region and jumping the δE_c barrier provided by the conduction band offset of adjacent regions. Furthermore, by minimizing the thickness of the hole confinement

region, excess optical loss related to inter-valence band absorption in sp^3 materials may be minimized. However, according to alternate embodiments of the current invention, other considerations comprising processing parameters or strain related issues may lead to DBR designs where the thickness of the hole confinement region is equal to or greater than the size of the electron confinement region. Similarly, according to alternate embodiments of the current invention, other considerations may lead to DBR designs comprising an electron confinement barrier δE_c created by the conduction band offset that is less than or equal to the hole confinement barrier δE_v created by the valence band offset.

FIG. 17 illustrates a band gap diagram and a layer structure for an alternate embodiment according to the current invention **400** comprising multiple thin electron confinement regions **413**, **415**, **417** and multiple thin hole confinement regions **412**, **414**, **416**. For this type of design, lattice matching may be a less important consideration due to the strain compensation that may take place in thin layers. Although FIG. 16 illustrates a DBR where the electron confinement layers are thicker than the hole confinement layers, alternate embodiments of the current invention may comprise layers providing electron and/or hole confinement regions of the same or varying thickness, compositions and/or electronic properties. Typically, the layers providing electron confinement regions would be adjacent to layers providing conduction band offset boundaries greater than the thermal energy, kT, and the layers providing hole confinement regions would be adjacent to materials providing valence band offset boundaries greater than kT. As previously discussed, preferably, the valence band offset boundaries and the conduction band offset boundaries are greater than 2kT.

For DBR **300** and **400**, sharp interfaces between the cladding layers, electron confinement regions and hole confinement regions are illustrated. In these examples, the barriers providing electron and hole confinement are created with sharply defined jumps in band gap energy levels. However, alternate embodiments of the current invention may provide valence band offset boundaries and conduction band offset boundaries using a variety of designs comprising graded materials and/or graded interfaces. For example, a layer of graded material may exist at one or more of the layer interfaces. FIG. 17 illustrates an alternate embodiment of the current invention with a graded electron confinement layer **812** and a graded hole confinement layer **813**. In this example, the energy level of the lowest conduction band and the energy level of the highest valence band vary across the thickness of the waveguide.

Furthermore, the cladding layers may comprise one or more layers of material with differing band gaps or graded material and still effectively achieve the purpose of a cladding layer. For example, FIGS. 18 and 19 illustrate band gap diagrams and layer structures for alternate embodiments of the current invention. For DBR **500**, electron-hole isolation is achieved using a graded layer **513** by varying the materials composition and band gap. Graded layer **513** creates an effective conduction band offset between the electron confinement layer **512** and the hole confinement layer **514** of δE_c **503**. Similarly, graded layer **513** creates an effective valence band offset between the electron confinement layer **512** and the hole confinement layer **514** of δE_v **505**.

In an alternate embodiment, a hole confinement region **612** and an electron confinement region **614** are created within a single graded layer **616** for DBR **600**. In this example, electron-hole confinement may be achieved through band structure tilting due to

the variation in materials composition across the waveguide. According to an alternate embodiment of the current invention, a local minimum energy level is established in the lowest level of the conduction band resulting in the creation of an electron confinement region **612**. In order to create an effective electron-hole barrier region for confining electrons in an alternative embodiment of the current invention such as DBR **600**, at least two criteria must be satisfied. First, the conduction band offset δEc **605** in the middle of the graded layer **616** must be much greater than the thermal energy, kT, at operating temperatures:

$$\delta Ec >> kT$$

Preferably, the average conduction band offset δEc **605** in the middle of the graded layer **616** is more than twice the thermal energy, 2kT, at operating temperatures:

$$\delta Ec > 2kT$$

Second, a sufficiently large electric field must be generated by the band structure tilting to offset the Coulombic forces driving the electrons and holes together. Based on the following approximation:

$$eN/(4\pi\varepsilon W^2) \leq \delta Ec/(eW),$$

the following design constraint may be adopted:

$$\delta Ec \geq e^2N/(4\pi\varepsilon W) \approx N/W,$$

where:

e = elementary charge

N = carrier concentration

ε = permittivity constant

W = thickness of the waveguide **616**

δEc= conduction band offset 605 in the middle of the graded layer **616**

Similarly, according to an alternate embodiment of the current invention, a local maximum energy level is established in the highest level of the valence band resulting in the creation of a hole confinement region **614**. In order to create an effective electron-hole barrier region for confining holes in an alternative embodiment of the current invention such as DBR **600**, at least two criteria must be satisfied. First, the valence band offset δEv **606** in the middle of the graded layer **616** must be much greater than the thermal energy, kT, at operating temperatures:

$$\delta Ev \gg kT$$

Preferably, the average valence band offset δEv **606** in the middle of the graded layer **616** is more than twice the thermal energy, 2kT, at operating temperatures:

$$\delta Ev > 2kT.$$

Second, a sufficiently large electric field must be generated by the band structure tilting to offset the Coulombic forces driving the electrons and holes together. Based on the following approximation:

$$eN/(4\pi\varepsilon W^2) \leq \delta Ev/(eW),$$

the following design constraint may be adopted:

$$\delta Ev \geq e^2N/(4\pi\varepsilon W) \approx N/W,$$

where:

e = elementary charge

N = carrier concentration

ε = permittivity constant

W = thickness of the waveguide **616**

δEv= valence band offset **606** in the middle of the graded layer **616**

FIG. 20 illustrates an alternate embodiment of the current invention using an intermediate barrier layer **713** to assist in the creation of electron-hole isolation. According to alternate embodiments of the current invention, one or more intermediate barrier layers may be used.

For the purposes of illustration, the band structures illustrated in FIGS. 15, 16, 17, 18, 19, and 20 are drawn in proper forward bias conditions. Typically, a DBR may be operated under a forward bias condition for optimal characteristics. In order to simplify the illustrations, neither the bias current nor the detailed band bending that may occur in the cladding layers has been illustrated.

Typical DBRs comprise grating layers. For example, FIG 21 illustrates a grating layer **885** in a cross sectional view of a typical DBR structure. In this example, a grating layer was created at the interface between the uppermost confinement layer **880** and the second cladding layer **890**. Typically, a grating layer may be created at the interface between two materials with differing indices of refraction. In this case, the grating layer comprises a ridged interface between layers **880** and **890**. In this case, a square profile

has been illustrated with a height of 100-200 nm. However, alternate embodiments of the current invention may comprise differing profiles. For example, an alternate embodiment of the current invention may comprise a grating with a sine wave profile. Typically, the period of the grating may be selected according to the wavelength range supported by the DBR. For example, for a DBR operating in the 1.55 μm region, a typical grating period may be approximately 235 nm. Alternate embodiments of the current invention may comprise a grating layer in alternate locations. For example, the grating may be located between the waveguide and the first cladding layer, between adjacent confinement regions in the waveguide, between the waveguide and the second cladding layer or on top of the second cladding layer. FIG 22 illustrates an alternate embodiment of the current invention with a grating layer comprised of grooves on the device surface. In this example, grooves may be created on the device top surface **1050**. In some cases, grooves may be created on the mesa top **1030** and/or mesa sidewalls **1040** instead of or in addition to the top surface grooves. Preferably, a grating layer may be created with holographic patterning techniques. However, alternate techniques may be used to create a grating layer such as e-beam lithography. Preferably, when a grating layer is buried in a DBR structure, such as grating layer **885**, subsequent layers, such as **890**, may be created using re-growth techniques.

FIG. 23 is a flow chart illustrating a method for creating a broadly tunable DBR. The method begins when the first cladding layer is created, as shown in step **910**. Preferably, the first cladding layer is deposited on a substrate using a technique such as MOCVD or MBE. According to an alternate method of the current invention, the first cladding layer may be grown from the substrate material or established using alternate

means such as ion implantation of the substrate material. According to the current invention, the first cladding layer may be n-type or p-type. Preferably, the process continues when the waveguide layer is created comprising one or more electron confinement regions and one or more hole confinement regions, as shown in step **920**. Typically, this may be achieved by the careful selection of composition profiles for the first cladding layer, waveguide layer and second cladding layer. Preferably, the compositional profile of the DBR may be based on the energy band diagrams of the materials comprising the cladding and confinement layers. According to some DBRs built according to the current invention, a DBR waveguide may be built by growing, depositing or re-growing one or more discrete layers of uniform composition. Alternately, some DBR waveguides built according to the current invention may be built by growing, depositing, re-growing one or more layers of varying composition or by creating one or more layers of uniform composition and then doping, diffusing or implanting additional material to compositional variation. Typical growth techniques may comprise conventional growth techniques such as MBE, CVD and/or MOCVD. In some cases, the process continues when a grating layer is created, as shown in step **930**. Preferably, a grating layer may be established by patterning and etching a grating on the top layer of the waveguide using conventional techniques. Preferably, holographic techniques may be used to establish the grating pattern. However, alternate techniques for creating a grating pattern such as e-beam lithography may be used. Subsequent deposition of a material with a differing index of refraction may complete the creation of a grating. Preferably, layers of material created after the creation of the grating layer may be re-grown instead of deposited. However, according to the current invention,

subsequent layers may be deposited. Preferably, the material comprising the second cladding layer may provide the source of material with a differing index of refraction. However, according to the current invention, an additional layer of material different from the second cladding layer may be used to provide the source of material with a differing index of refraction. In some cases, the grating layer may be established at an earlier or later step in the process. For example, a grating layer may be established between the first cladding layer and the waveguide, in the waveguide between adjacent confinement regions or on top of the DBR device surface. Preferably, the process continues when the second cladding layer is created, as shown in step **920**.

Steps **910**, **920**, **930**, **940** and **950** may be rearranged depending on the design of the broadly tunable distributed Bragg reflector and/or the specific manufacturing processes used. For example, some DBR designs may include an optical waveguide comprising alternating electron confinement layers and hole confinement layers wherein the first layer of the optical waveguide is an electron confinement layer. Alternately, some DBR designs may include an optical waveguide comprising alternating electron confinement layers and hole confinement layers wherein the first layer of the optical waveguide is a hole confinement layer. Alternately, some DBR designs may comprise differing numbers of hole confinement layers and electron confinement layers.

Optionally, one or more additional process steps such as, but not limited to lithography, patterning, deposition, growth, annealing and etching may be incorporated into the process according to the current invention. For example, laser devices, integrated electro-optical devices and/or more complex optical devices may be built by adding conventional processing steps to the preferred method according to the current invention.

Optional Step **960** illustrates one example of an additional conventional process step added after the process steps according to a preferred method according to the current invention have been completed. Optionally, alternate methods according to the current invention may incorporate one or more of the additional conventional processing steps between, before and/or after the preferred process steps according to the current invention.

For FIGS. 15-23, although the term DBR is used to describe a laser structure, the description is equally applicable to VCSEL and DFB laser structures. In addition, the characterization of the DBR can also be referred to as a carrier reservoir structure, as used in describing FIGS. 1-14.

The foregoing described embodiments of the invention are provided as illustrations and descriptions. They are not intended to limit the invention to precise form described. In particular, the Applicants contemplate that functional implementation of the invention described herein may be implemented equivalently in hardware, software, firmware, or other available functional components or building blocks. Specifically, figures and descriptions show variation of energy band structure and materials composition in two dimensions. However, it is contemplated that the energy band structures and/or materials compositions may vary in three dimensions. Also, the process steps describing the methods may be re-arranged and/or re-ordered. Other variations and embodiments are possible in light of above teachings, and it is thus intended that the scope of invention not be limited by this Detailed Description, but rather by Claims following.